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# Reduced Pressure Electron Beam Welding Evaluation Activities on a Ni-Cr-Mo Alloy for Nuclear Waste Packages

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**Abstract** – *The current waste package design for the proposed repository at Yucca Mountain Nevada, USA, employs gas tungsten arc welding (GTAW) in fabricating the waste packages. While GTAW is widely used in industry for many applications, it requires multiple weld passes. By comparison, single-pass welding methods inherently use lower heat input than multi-pass welding methods which results in lower levels of weld distortion and also narrower regions of residual stresses at the weld. TWI Ltd. has developed a Reduced Pressure Electron Beam (RPEB) welding process which allows EB welding in a reduced pressure environment (≤ 1 mbar). As it is a single-pass welding technique, use of RPEB welding could (1) achieve a comparable or better materials performance and (2) lead to potential cost savings in the waste package manufacturing as compared to GTAW. Results will be presented on the initial evaluation of the RPEB welding on a Ni-Cr-Mo alloy (a candidate alloy for the Yucca Mountain waste packages) in the areas of (a) design and manufacturing simplifications, (b) material performance and (c) weld reliability.*

## I. INTRODUCTION

The current YMP waste package design employs gas tungsten arc welding (GTAW) in fabricating the waste package for both the Ni-Cr-Mo alloy, Alloy 22 (UNS N06022), outer barrier and 316NG inner shell [1]. While GTAW is widely used in industry for many applications, it requires multiple weld passes (e.g. ~8 passes are required for the Alloy 22 outer barrier) which will produce weld distortions and regions of tensile residual stresses at the surface. By comparison, single-pass welding methods inherently use lower heat input which results in lower levels of weld distortion and also narrower regions of residual stresses at the weld.

Electron beam (EB) welding is also widely used in industry and typically results in faster welding times (as it is a single-pass method) and a more favorable distribution of residual stresses. However, conventional EB welding usually requires the work piece to be contained in a good vacuum environment during welding. TWI Ltd. has developed a Reduced Pressure Electron Beam (RPEB) welding process which allows EB welding in a reduced pressure environment (≤ 1 mbar) achieved by local sealing and pumping. The RPEB method has been used by SKB (Swedish nuclear waste program) in their waste package mockup program (~40 canister mockups fabricated with RPEB welding since 1992).

If such a single-pass welding technique could be used in fabricating the YMP waste packages, potential cost savings would be significant and would primarily result from:

- Elimination of weld filler metal
- Faster welding times
- Elimination of plate overstock
- Reduced machining times
- More favorable distribution of residual stresses

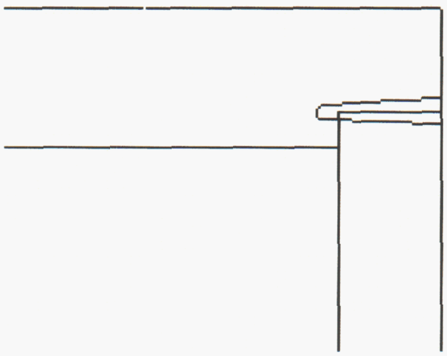
In summary, the use of RPEB welding for waste package fabrication would provide the following potential benefits to the Yucca Mountain program: 1) significant cost savings in waste package manufacturing, 2) equal or better materials performance in terms of corrosion, metallurgical stability, and as-welded residual stress from a single-pass welding process, 3) increased repeatability and reliability in waste package welding due its single-pass nature.

A comparison of GTAW and RPEB welds in Ni-Cr-Mo alloys is shown in Figure 1 and described in Table 1.

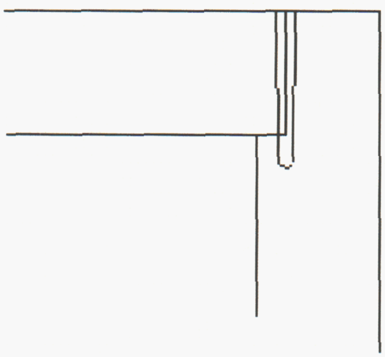
TABLE 1
Brief Comparison of RPEB welding and GTAW for YMP waste packages

| | **Reduced Pressure Electron Beam Welding** | **Gas Tungsten Arc Welding** |
|---|---|---|
| Welding Speed | Welding speed > 250 mm/min. Could be in excess of 1000 mm/min for single pass in 30 mm thickness material | Typically <~150 mm/min per pass: minimum root pass + 9 passes to complete 30 mm. Therefore, > 10X joint completion rate disadvantage. Interpass temperature control for GTAW important. Need to avoid precipitation of non-equilibrium intermetallic phases. |
| Weld Preparation Geometry | Simple square butt-edge preparation | Root face detail and narrow gap preparation for GTAW |
| Weld Seam Tracking | Real-time seam tracking minimises risk of missed joint defects. | Care required for avoidance of side wall and inter run lack of fusion defects |
| Weld Tolerances | Demonstrated tolerance to fit-up on similar structures | Similar or more exacting fit-up required for GTAW |
| Weld Consumables | Autogenous welding – no consumable requirement (except small quantity of He gas) Cost saving on procurement and QC of filler metal and shielding gas. Vacuum/He atmosphere provides effective shielding cap and root. Filler material can be added if required | Quality assured filler wire and process gas required |
| Weld Inspection | Inspection of square butt-joint: Radiography and UT in combination with surface flaw detection gives good reliability and probability of detection and sizing possibility | UT inspection and interpretation more difficult on beveled joint and detection of lack of inter-run and sidewall fusion difficult with narrow gap GTAW joint. Tungsten inclusions can be introduced |
| Welding Process | Fully-automatic, largely electrical process with possibilities for in-process monitoring and reactive control. Process reliability minimizes repairs and in-process monitoring encourages well-targeted inspection. Repairs can be realized without excavation by simple re-runs | Fully-automatic, largely electrical process with possibilities for in-process monitoring and reactive control. Repairs generally require excavation. |
| Weld Productivity | Process speed leads to great potential productivity advantage | Welding productivity can be improved by the use of several welding stations. For closure welding this entails more hot cells. |
| Segregation in Weld | Single-pass welding avoids potential difficulties with interpass temperature control and confidence in avoidance of hot cracking. Segregation likely to be similar to GTAW | Potential advantage in predicted consistency of (very localized, short range) residual stresses and predictable segregation allowing confident corrosion modeling and modeling of other degradation modes |
| Residual Stresses Near Weld | Single-pass nature also may result in lower residual stresses at the weld, which may allow simplified stress mitigation methods for minimizing the potential for stress corrosion cracking | Resulting residual stresses at the weld require stress mitigation techniques to minimize potential of stress corrosion cracking |
| Use in Hot Cell Environment | Tolerance of equipment to high radiation flux levels. Long life, low maintenance system Automatic, remote non-contact process avoiding many hot cell related difficulties and high productivity reduces number of hot cells required. | GTAW requires filler wire delivery, shielding gas and a tungsten electrode, all in the hot cell, immediately adjacent to the weld joint. Equipment needs to be specially designed to be sufficiently robust for long a welding campaigns in such a hostile an environment. Special arrangements are required for the regular equipment maintenance |
| Experience | Demonstrated nuclear waste and fuel encapsulation experience | Mature welding technology, with many safety critical references |

of the lid including a final evacuation and back purging process [1]. RPEB welding of the Alloy 22 outer barrier could simplify this process in that a simple weld preparation detail can be employed, and the welding operation itself will result in an inert atmosphere inside the canister. The joint detail is sufficiently flexible to allow welding to be performed either horizontal–vertical welding position, or down-hand, Figure 3.



(a)



(b)

Figure 3 Detail of proposed RPEB lid weld preparation: (a) Horizontal-Vertical position and (b) down-hand position

In each case the lid is self-locating on the waste package and requires only simple machining to achieve the necessary fit up. RPEB welding in the horizontal-vertical welding position has been demonstrated by the Swedish waste management company (SKB) for closure of copper high-level nuclear waste packages, (Figure 4)

Due to their experience with the SKB, TWI Ltd. has developed a modular RPEB welding system that is easily deployed and maintained in a hot cell environment. The RPEB welding system has been designed to employ a standoff distance of 50 to 500 mm. Thus, all of the RPEB welding system electronic components can be maintained outside of the welding hot cell.

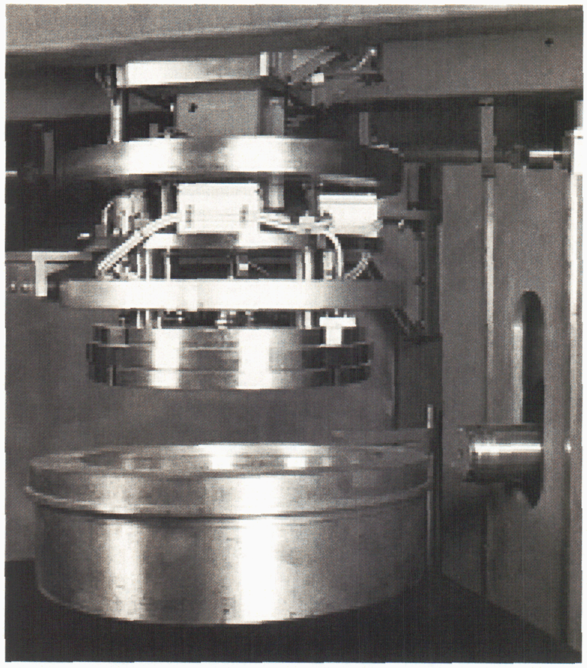


Figure 4 Arrangement for closure of copper high-level nuclear waste package using RPEB welding (courtesy of SKB)

## IV. MATERIAL PERFORMANCE

To assess the material performance benefits of the RPEB welding process, a comprehensive comparative evaluation of GTAW and RPEB weld samples is being performed. For the application at Yucca Mountain, metallurgical stability, corrosion behavior, and as-welded residual stresses are the key long-term materials performance factors.

### *IV.A. Metallurgical Evaluations*

The initial microstructural analyses of GTAW and RPEB weld samples examined weld morphology and compositional analyses using EMPA (Electron Microprobe Analyses). In the GTAW samples, matching Alloy 22 filler metal was used, while in the RPEB samples, no filler metal used. In the examinations performed to date, both welds exhibit similar microstructures.

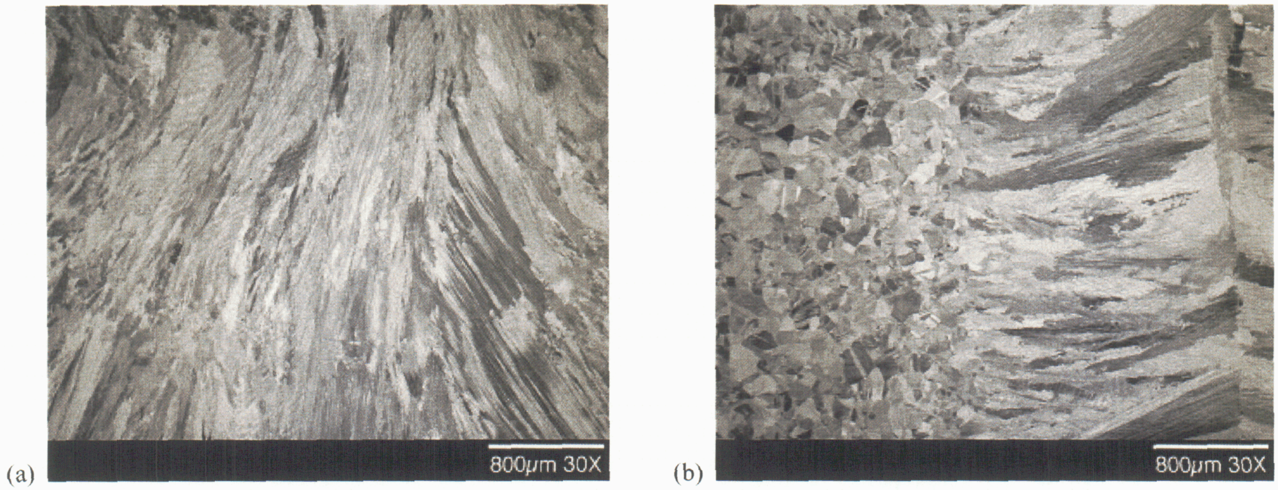



Figure 5 Micrographs showing dendrite structures as a result of heat flow in (a) GTAW sample (base metal near right edge) and (b) RPEB weld (base metal near left edge)

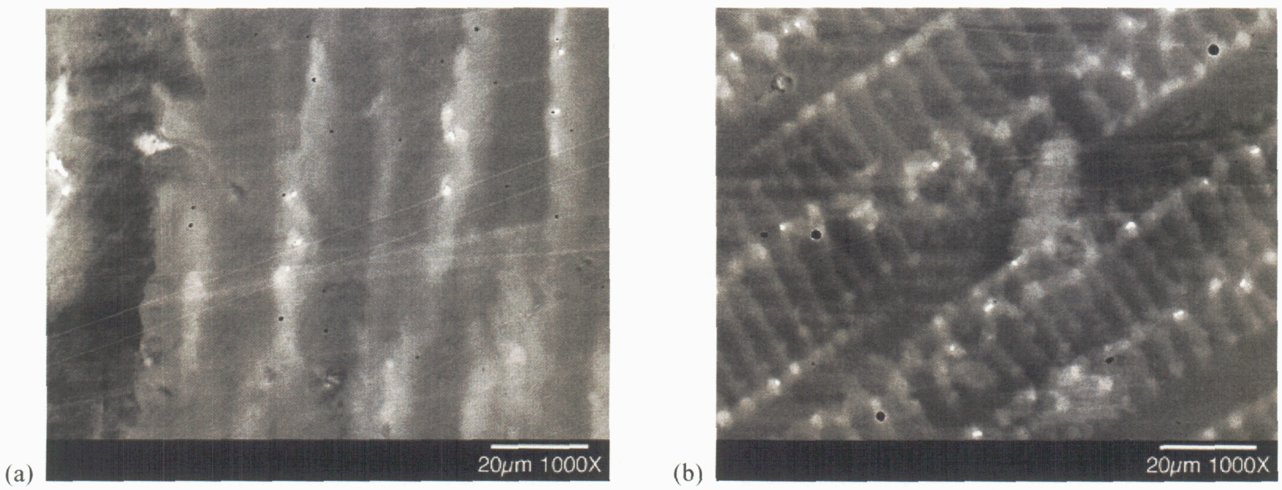
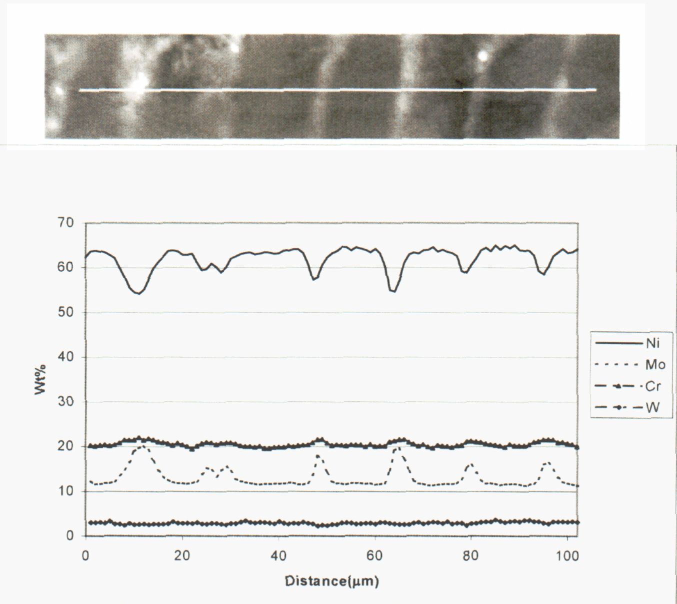


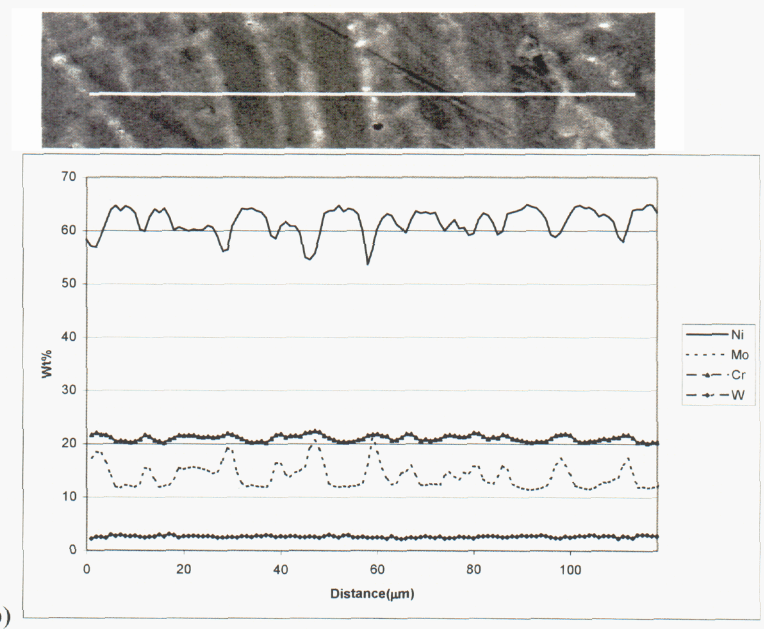

Figure 6 Micrographs showing detailed dendrite structures, including secondary dendrites, in (a) GTAW sample and (b) RPEB weld.

The weld dendrite structure and heat flow patterns are shown in Figures 5 and 6. The heat flow patterns from GTAW result in near vertical dendrite patterns (Figure 5a). The mostly finer dendrite patterns from RPEB welding are indicative of a faster cooling rate as compared to GTAW [4]. The higher magnification images in Figure 6 confirm the dendrite orientation and also reveal distinct secondary dendrite formation in the RPEB weld. RPEB welding appears to create a finer dendrite spacing than GTAW.

EPMA scans have been conducted to determine the compositional variations of Ni, Cr, Mo, and W across the weld region and are summarized in Figure 7. The scans showed that for both GTAW and RPEB welds, Cr and W levels remain relatively constant across the weld region, with W exhibiting a mostly flat profile. However, a few randomly distributed W-rich particles were observed (bright spots in Figure 6) at the dendrite boundaries. As expected, the EPMA scans also showed regions of Mo enrichment corresponding with Ni depletion across the weld. The lighter regions of the electron backscatter images are indicative of regions of Mo enrichment (and hence, Ni depletion), as shown in Figure 7. Minor differences in the magnitude of the variations in Mo and Ni levels in the GTAW and RPEB weld samples are observed.




(a)




(b)

Figure 7 EPMA scans for (a) GTAW and (b) RPEB welded samples. Lighter regions exhibited Mo enrichment and Ni depletion. Both Cr and W levels remained relatively constant across the scanned region (W exhibited the most constant profile).

### *IV.B. Corrosion Performance*

Corrosion is the dominant degradation mode for the Yucca Mountain waste packages. As a result, studies are underway to examine the relative corrosion resistance of Alloy 22 in three conditions: (1) base metal, (2) GTAW and (3) RPEB. The general and localized corrosion studies of the three types of material were carried out in three different electrolyte solutions. These were Simulated Concentrated Water (SCW), One Molar Hydrochloric Acid (1 M HCl) and One Molar Sodium Chloride (1 M NaCl) solutions. SCW was used as a representative environment of Yucca Mountain since SCW is approximately 1000 times more concentrated than the well J-13 water from near Yucca Mountain. SCW is slightly alkaline (pH between 8 and 10). The 1 M HCl at 60°C environment was used since it can etch welds under positive polarization. The pH of 1 M HCl is zero (highly acidic). The saline solution 1 M NaCl at 90°C was used since it is one of the least aggressive environments that can still promote crevice corrosion in Alloy 22 at anodic applied potentials. The pH of 1 M NaCl is near neutral.

To date, three types of corrosion tests have been conducted thus far: polarization resistance, cyclic potentiodynamic polarization, and galvanostatic tests. The corrosion rates (CR) were obtained using the polarization resistance method (ASTM G 59). Tests to assess the susceptibility of the Alloy 22 welds to localized corrosion and passive stability were conducted using the cyclic potentiodynamic polarization technique (ASTM G 61). After the cyclic polarization tests the specimens were examined in an optical stereomicroscope at a 40X magnification to establish the mode of attack. Selected specimens were also imaged using a scanning electron microscope (SEM). One specimen of each weld type (GTAW and RPEB) was also subjected to galvanostatic (constant current density) testing in the HCl solution to reveal weld areas that were more susceptible to corrosion.

The relative corrosion rates for the three materials (GTAW, RPEB and Base metal) in the three tested solutions are summarized in Figure 8. The corrosion rate in the 1 M HCl solution was approximately two orders of magnitude higher than in the other two less aggressive solutions. The overall lowest corrosion rates were for the 1 M NaCl solution on creviced specimens. For the GTAW and RPEB specimens, the corrosion rates are similar.

For each solution, the cyclic polarization curves appear almost undistinguishable from each other for the three types of material (GTAW, RPEB and base). Figure 9 shows that for the SCW at 90°C solution, the cyclic polarization curves for all the materials show an anodic peak on the forward sweep at a potential of approximately 250 mV (SSC) with a current density between 350 to 550 $\mu A/cm^2$. The highest current density was for the base material and the lowest for the GTAW specimen. The origin of these peaks is still unknown. There is also some noise in the final portion of the reverse scan where it crosses the forward passive region. The origin of this noise is also not known. Even though Figure 9 shows a small hysteresis in the reverse potential scanning, none of the materials tested in SCW at 90°C showed localized corrosion.

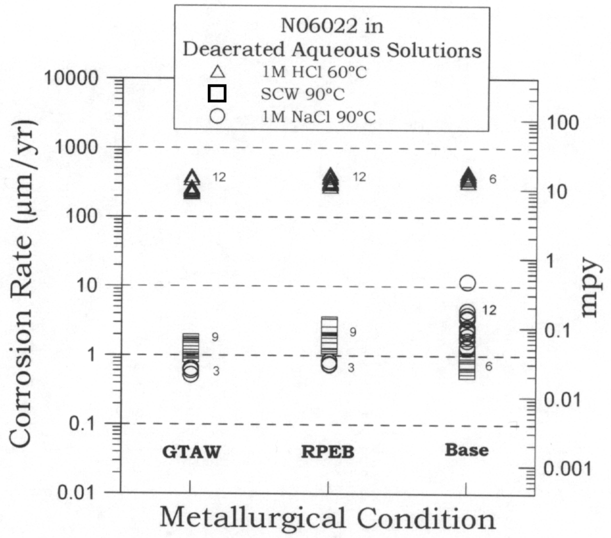



Figure 8 Comparative corrosion rates for GTAW, RPEB weld, and base metal specimens in SCW, 1M HCl, and NaCl solutions. The small numerals next to the symbols indicate the number of individual points in each cluster.

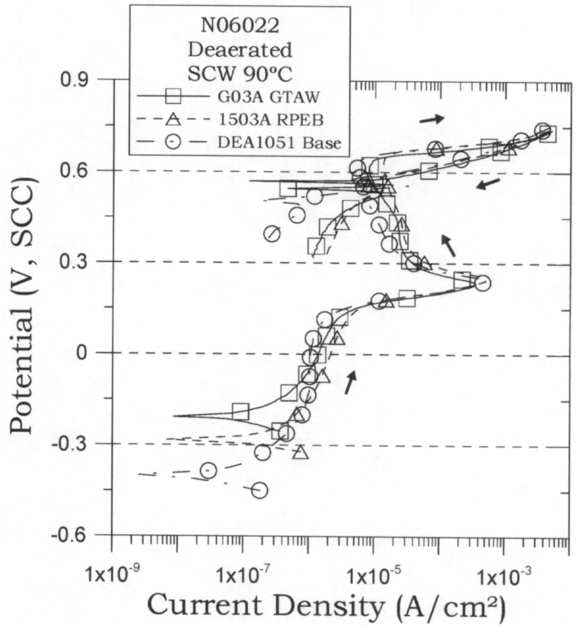



Figure 9 Cyclic polarization curves for the two Alloy 22 weld types and base metal in deaerated 90°C SCW. Arrows indicate the direction of curve trace as the test proceeds.

Scanning electron microscope (SEM) images of the corroded GTAW and RPEB welded specimens after the galvanostatic treatment are shown in Figures 10 and 11. Initial observations on the weld microstructures after the galvanostatic tests showed that for both the GTAW and RPEB weld samples, the corrosion patterns correlate well with regions of Mo and Ni depletion/enrichment along the dendrites. Thus, by forcing the alloy to corrode at a constant current density, the corrosion appears to occur along observed microstructural features.

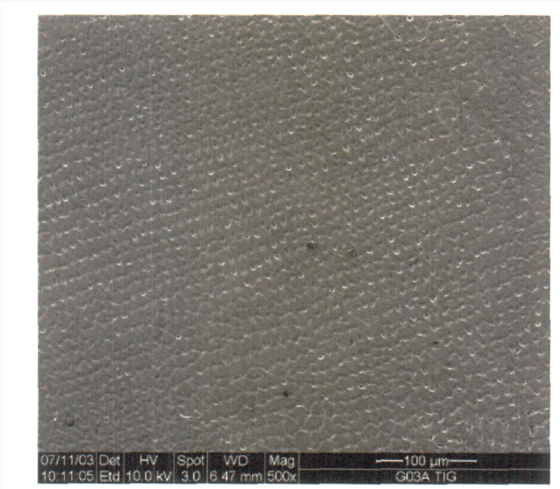



Figure 10 Corroded surface of GTAW specimen (G03A) after 1 mA/cm² galvanostatic testing in 1 M HCl at 60°C for 3 h, (500 X magnification)

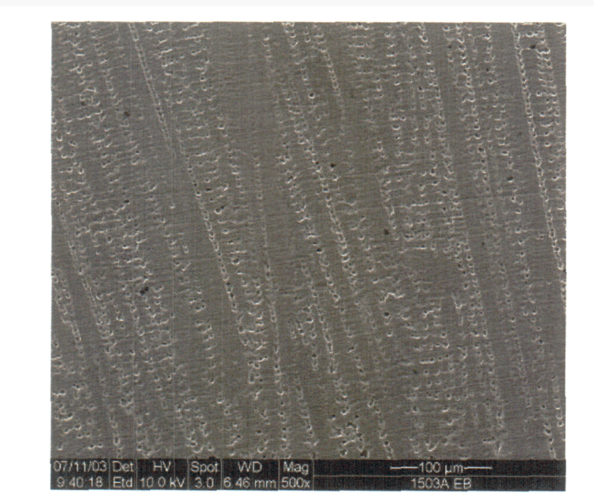



Figure 11 Corroded surface of RPEB specimen (1503A) after 1 mA/cm² galvanostatic testing in 1 M HCl at 60°C for 3 h (500X magnification).

*IV.C. As-Welded Residual Stress Measurements*

Stress corrosion cracking is a primary concern for the long-term materials performance of the Yucca Mountain waste packages. Stress corrosion cracking may occur when three factors are simultaneously present: a susceptible alloy, an applicable environment, and tensile residual surface stresses. In order to minimize the potential for stress corrosion cracking, the Yucca Mountain waste package design seeks to minimize tensile residual surface stresses in the final closure weld area (the only weld which will not undergo a solution anneal).

As shown in residual stress contour maps [3] of Figure 2, the peak tensile residual stress (longitudinal component) in the GTAW sample is near the surface, while in the RPEB weld, it is near mid-thickness of the sample. In the case of GTAW, the peak tensile residual stress will always be near the surface of the weld due to the multi-pass weld process. As the earlier weld passes cool, these passes aid in restraining the "V" groove geometry during cooling of successive passes. Thus, the peak tensile residual stress will be near the surface of the last pass. On the other hand, with RPEB welding, since it is a single-pass process, the peak tensile residual stress will be near mid-thickness of the weld region, as the top surface will cool faster than the middle region. In addition, the distribution of tensile residual stresses from RPEB welding will have a narrower profile than GTAW (Figure 2). In Figure 12, RPEB welding is shown to have peak tensile residual surface stress (longitudinal component) about 75% less than GTAW. It is expected that optimization of the RPEB welding parameters lead to further reductions in tensile residual surface stresses.

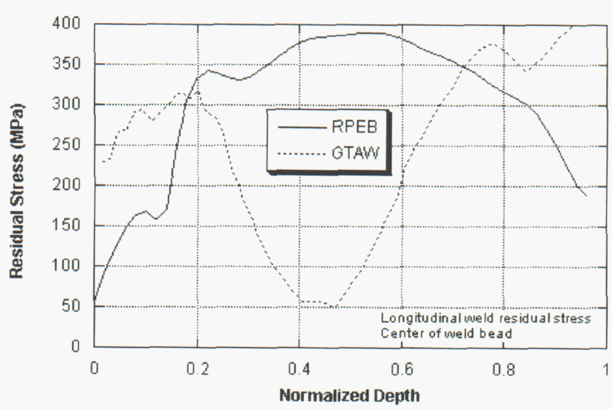



Figure 12 Residual stress profiles (longitudinal component) as function of plate depth at the center of the weld bead for GTAW and RPEB welding samples. RPEB welding is exhibits a peak tensile residual surface stress about 75% less than GTAW.

In order to reduce the level of tensile residual surface stresses in the closure weld region, and hence, the potential for stress corrosion cracking, the current waste package design uses laser peening to induce compressive residual surface stresses. Mitigation of tensile residual

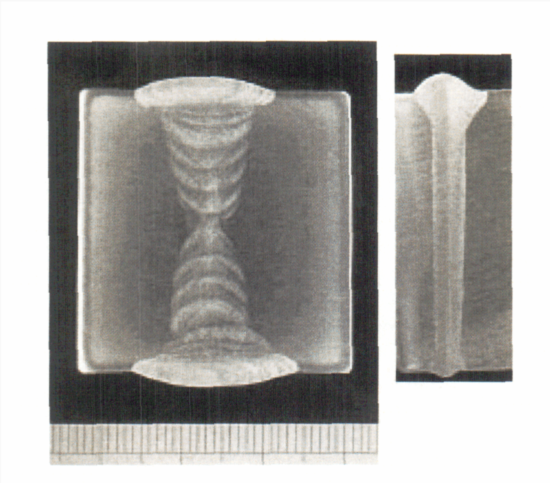


Figure 1 Multi-Pass GTAW (Left) and Single-Pass RPEB (Right) Welds in Ni-Cr-Mo-W Alloys

## II. POTENTIAL COST SAVINGS OF RPEB WELDING

RPEB welding would provide the following significant cost savings in waste package fabrication:

*Elimination of weld filler metal:* Unlike the GTAW process, filler metal is not essential in the RPEB welding process.

*Faster welding time:* RPEB welding has a faster travel speed than GTAW. In addition, the RPEB welding process is a single-pass welding method, whereas GTAW requires multiple passes. Table 2 compares the estimated welding times of GTAW and RPEB welding for the final waste package closure lid, but these faster welding times for RPEB welding would also be applicable to all welds in the waste package. Use of RPEB welding for waste package fabrication is estimated to be about 30 times faster than GTAW.

TABLE 2
Comparison of Estimated Welding Times for GTAW and RPEB Welding for Alloy 22

| | **Travel speed** | **Weld Passes** | **Closure Lid - Welding Time** |
|---|---|---|---|
| | (mm/min) | (#) | (min) |
| GTAW [2] | 200 | 8 | 251.3 |
| RPEBW | 750† | 1 | 8.4 |

† Actual weld speed for representative Alloy 22 test plate (performed by TWI Ltd., November 2002)

*Elimination of plate overstock:* The GTAW process produces a larger amount of weld distortion than RPEB welding primarily due to (1) its multi-pass welding process and (2) the "V" geometry of weld groove design. As a result with GTAW, slightly thicker plates must be welded into a cylinder, and the cylinder would then be machined to compensate for weld distortion and ensure a final circular cross section. RPEB welding, since it is single-pass process and uses a simple "flat-edge" weld geometry, results in much less weld distortions.

*Reduced final machining times:* The final machining of the waste packages are required to correct for any distortions due to welding for both the Alloy 22 outer barrier and 316NG inner shell. The RPEB welding process results in a lower amount of weld distortion compared to GTAW primarily due to (1) its single-pass nature which results in lower heat input, and (2) its use of simple "flat-edge" weld groove geometry, whereas, GTAW usually employs a "V"-type weld groove. Thus, the final machining times after RPEB welding will be shorter than those following GTAW.

*More favorable distribution of residual stresses:*
All welding processes result in residual tensile stresses in or near the welded regions due to weld solidification. The level of tensile residual stresses, especially at the weld surface, is a primary factor for initiation of stress corrosion cracking in the waste package closure weld. RPEB welding has shown to produce narrower regions and a lower level of tensile residual surface stresses (~75% less) due to its single-pass characteristics (Figure 2), as compared to GTAW. Thus, the use of RPEB welding may reduce the level and extent of stress mitigation techniques that would be applied to the closure weld region of the waste package.

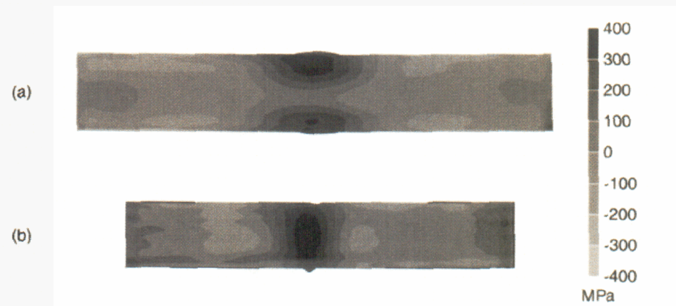



Figure 2 Longitudinal (weld direction) residual stress contour plots [3] in the as-welded condition for the (a) GTAW and (b) RPEB weld samples similar to those shown in Figure 1.

## III. DESIGN AND MANUFACTURING SIMPLIFICATIONS

The current proposal for final closure of the waste package involves several operations for closure welding surface stresses in the closure weld region would delay the initiation of stress corrosion cracking. Since RPEB welding produces a more favorable residual stress distribution for minimizing the potential for stress corrosion cracking, the level and extent of stress mitigation techniques applied to the closure weld region may be reduced with RPEB welding. The residual stress contour (longitudinal component) of a RPEB weld before and after laser peening [5] is shown in Figure 13. As expected, laser peening induces compressive residual surface stresses and a flatter profile of residual stress across the weld.

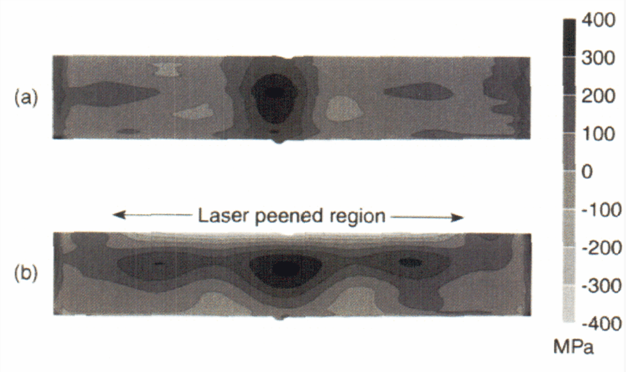



Figure 13 Comparison of residual stress contours [3] (longitudinal component) for RPEB welds (a) in the as-welded condition and (b) after laser peening. NOTE: These samples were too short to contain a fully developed residual stress field and thus the as-welded stresses are less than those shown in Figure 2.

## V. WELD RELIABILITY

EB welding is a mature technology which has been employed extensively in many safety critical applications in both the aeroengine and nuclear industries for more than four decades. The process can be fully automated and once appropriate weld procedures are in place, weld reliability depends almost solely on ensuring that the beam is suitably aligned with the joint and that there is no interruption to the process or change in the beam characteristics. Experience in operating at the Reduced Pressure EB process variant at TWI has illustrated that the process is particularly tolerant. The system incorporates a real-time seam tracking feature based on back scattered electron detection which uses the beam itself to locate and follow the seam, taking account of any thermal expansion, distortion and machining inaccuracies. The system has been designed specifically to accommodate high duty cycle high power welding campaigns and as such requires infrequent maintenance and provides long-term stable beam quality and thus welding consistency. Operation at Reduced Pressure has the added advantages of huge tolerance to variations in gun to work distance, fit-up and immunity to high voltage breakdown or gun flashover.

Producing welds autogenously in a single pass has the added benefit of simplicity of joint preparation and the absence of wire feed systems which inherently leads to better process reliability.

## VI. CONCLUSIONS

Initial evaluation of RPEB welding for fabrication of Yucca Mountain waste packages indicates that it provides similar performance to GTAW in terms of corrosion behavior and Mo/Ni segregation characteristics. These evaluations have also shown that RPEB may result in a more favorable distribution of as-welded residual stresses as compared to GTAW. In addition, the inherent characteristics of RPEB, especially the ability to make single-pass welds with reduced distortion, will offer the potential for significant cost reduction.

## ACKNOWLEDGMENTS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